Simple predictions from ALCOR$_c$ for rehadronisation of charmed quark matter

P. Lévai, T.S. Biró, T. Csörgő, J. Zimányi

RMKI Research Institute for Particle and Nuclear Physics,
P. O. Box 49, Budapest, 1525, Hungary

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Abstract

We study the production of charmed hadrons with the help of ALCOR$_c$, the algebraic coalescence model for rehadronisation of charmed quark matter. Mesonic ratios are introduced as factors connecting various antibaryon to baryon ratios. The resulting simple relations could serve as tests of quark matter formation and coalescence type rehadronization in heavy ion collisions.

Charm hadron production has gained an enhanced attention in relativistic heavy ion collisions at CERN SPS (Super Proton Synchrotron). The measured anomalous suppression of the J/ψ in Pb+Pb collision [1] is considered as one of the strongest candidates for an evidence of quark-gluon plasma (QGP) formation in Pb+Pb collision at 158 GeV/nucleon bombarding energy [2]. So far only the J/ψ and ψ' production was measured in heavy ion collisions through dilepton decay channels. However, recent efforts to measure D-meson [3, 4] support the theoretical investigation of charm production from a different point of view. Namely, it is interesting to search for predictions on the total numbers of charmed hadrons and their ratios. The answer to this question may become very important at the RHIC accelerator, where a large number of charmed quark-antiquark pairs will be produced and a number of different charmed hadrons could be detected.

In this paper we assume that quark matter is formed in heavy ion collisions and the charm hadrons will be produced directly from this state via quark coalescence. Quark coalescence was successfully applied to describe direct hadron production from deconfined quark matter phase (see. the ALCOR [5, 6], the Transchemistry [7] and the MICOR [8] models). In these models the hadronic rescatterings are assumed to be weak and they are neglected. Thus the results of quark coalescence processes were compared directly to the experimental data - and the agreement was remarkably good.

Multicharm hadron production was already investigated in a simplified quark coalescence model and first results were obtained at RHIC and LHC energies, where an appreciable number of charm quark may appear [9]. Here we summarize simple predictions from a non-linear algebraic coalescence model ALCOR$_c$, the extension of the ALCOR model of algebraic coalescence of strange quark matter [5, 6] for the inclusion of charmed quarks, mesons and baryons.

The description of the charmed baryons has to deal with the fact that two possible $(1/2)^+$ baryon multiplets exist containing c, s and u (or d) quarks, one being flavor symmetric under s and d (or u) exchange and the other being antisymmetric [10]. The heavier (symmetric) states decay into the lighter (antisymmetric) one by emission of a γ or a π meson. However, if quark clusterization is the basic hadronization process, then the effect of these decay processes will be cancelled from charmed antibaryon to baryon ratios. Neglecting the difference between the light u and d quarks and using the notation q for them, the 10 different types of produced quark clusters can be connected to the 40 lowest lying SU(4)-flavor baryon species in the following way (see e.g. Ref. [11, 12] for precise quark content, hadron names and masses):

$$
\begin{aligned}
N(qqq) &:= p,\ n,\ \Delta^{++},\ \Delta^{+},\ \Delta^{0},\ \Delta^{-}\ ; \\
Y(qqs) &:= \Lambda^{0},\ \Sigma^{+},\ \Sigma^{0},\ \Sigma^{-},\ \Sigma^{*+},\ \Sigma^{*0},\ \Sigma^{*-}\ ; \\
\Xi(qss) &:= \Xi^{0},\ \Xi^{-},\ \Xi^{*0},\ \Xi^{*-}\ ; \\
\Omega(sss) &:= \Omega^{-}\ ; \\
Y_c(qqc) &:= \Lambda_c^{+},\ \Sigma_c^{++},\ \Sigma_c^{+},\ \Sigma_c^{0},\ \Sigma_c^{*++},\ \Sigma_c^{*+},\ \Sigma_c^{*0}\ ; \\
\Xi_c(qsc) &:= \Xi_c^{+},\ \Xi_c^{0},\ \Xi_c{}'^{+},\ \Xi_c{}'^{0},\ \Xi_c^{*+},\ \Xi_c^{*0}\ ; \\
\Omega_c(ssc) &:= \Omega_c^{0},\ \Omega_c^{*0}\ ; \\
\Xi_{cc}(qcc) &:= \Xi_{cc}^{+},\ \Xi_{cc}^{++},\ \Xi_{cc}^{*+},\ \Xi_{cc}^{*++}\ ; \\
\Omega_{cc}(scc) &:= \Omega_{cc}^{+},\ \Omega_{cc}^{*+}\ ; \\
\Omega_{ccc}(ccc) &:= \Omega_{ccc}^{++}
\end{aligned}
\tag{1}
$$

In ALCOR, the algebraic coalescence model of rehadronization it is assumed that the number of directly produced hadrons is given by the product of the the number of quarks (or anti-quarks) from which those hadrons are produced, multiplied by coalescence coefficients C_h and by non-linear normalization coefficients b_q, that take into account conservation of quark numbers during quark coalescence, as will be explained subsequently. The number of various hadrons and quarks is denoted by the symbol usual for that type of particles, e.q. q, s and c denote the number of light, strange and charmed quarks, respectively, N denotes the number of protons, neutrons and deltas etc.

In this way the baryons and antibaryons can be described through the following clustering relations:

$$
\begin{aligned}
N\,(qqq) &= C_N \cdot (b_q\,q)^3 & \overline{N}\,(\overline{qqq}) &= C_{\overline{N}} \cdot (b_{\overline{q}}\,\overline{q})^3 \\
Y\,(qqs) &= C_Y \cdot (b_q\,q)^2 \cdot (b_s\,s) & \overline{Y}\,(\overline{qqs}) &= C_{\overline{Y}} \cdot (b_{\overline{q}}\,\overline{q})^2 \cdot (b_{\overline{s}}\,\overline{s}) \\
\Xi\,(qss) &= C_\Xi \cdot (b_q\,q) \cdot (b_s\,s)^2 & \overline{\Xi}\,(\overline{qss}) &= C_{\overline{\Xi}} \cdot (b_{\overline{q}}\,\overline{q}) \cdot (b_{\overline{s}}\,\overline{s})^2 \\
\Omega\,(sss) &= C_\Omega \cdot (b_s\,s)^3 & \overline{\Omega}\,(\overline{sss}) &= C_{\overline{\Omega}} \cdot (b_{\overline{s}}\,\overline{s})^3 \\
Y_c\,(qqc) &= C_Y^c \cdot (b_q\,q)^2 \cdot (b_c\,c) & \overline{Y}_c\,(\overline{qqc}) &= C_{\overline{Y}}^c \cdot (b_{\overline{q}}\,\overline{q})^2 \cdot (b_{\overline{c}}\,\overline{c}) \\
\Xi_c\,(qsc) &= C_\Xi^c \cdot (b_q\,q) \cdot (b_s\,s) \cdot (b_c\,c) & \overline{\Xi}_c\,(\overline{qsc}) &= C_{\overline{\Xi}}^c \cdot (b_{\overline{q}}\,\overline{q}) \cdot (b_{\overline{s}}\,\overline{s}) \cdot (b_{\overline{c}}\,\overline{c}) \\
\Omega_c\,(ssc) &= C_\Omega^c \cdot (b_s\,s)^2 \cdot (b_c\,c) & \overline{\Omega}_c\,(\overline{ssc}) &= C_{\overline{\Omega}}^c \cdot (b_{\overline{s}}\,\overline{s})^2 \cdot (b_{\overline{c}}\,\overline{c}) \\
\Xi_{cc}\,(qcc) &= C_\Xi^{cc} \cdot (b_q\,q) \cdot (b_c\,c)^2 & \overline{\Xi}_{cc}\,(\overline{qcc}) &= C_{\overline{\Xi}}^{cc} \cdot (b_{\overline{q}}\,\overline{q}) \cdot (b_{\overline{c}}\,\overline{c})^2 \\
\Omega_{cc}\,(scc) &= C_\Omega^{cc} \cdot (b_s\,s) \cdot (b_c\,c)^2 & \overline{\Omega}_{cc}\,(\overline{scc}) &= C_{\overline{\Omega}}^{cc} \cdot (b_{\overline{s}}\,\overline{s}) \cdot (b_{\overline{c}}\,\overline{c})^2 \\
\Omega_{ccc}\,(ccc) &= C_\Omega^{ccc} \cdot (b_c\,c)^3 & \overline{\Omega}_{ccc}\,(\overline{ccc}) &= C_{\overline{\Omega}}^{ccc} \cdot (b_{\overline{c}}\,\overline{c})^3
\end{aligned}
\tag{2}
$$

Mesons in the pseudoscalar and vector SU(4)-flavor multiplets are grouped in the following way:

$$\begin{aligned}
\pi(q\overline{q}) &:= \pi^+,\ \pi^0,\ \pi^-,\ \eta,\ \rho^+,\ \rho^0,\ \rho^-,\ \omega; \\
K(q\overline{s}) &:= K^+,\ K^0,\ K^{*+},\ K^{*0}; \\
\overline{K}(\overline{q}s) &:= K^-,\ \overline{K}^0,\ K^{*-},\ \overline{K}^{*0}; \\
\phi(s\overline{s}) &:= \eta',\ \phi; \\
D(\overline{q}c) &:= D^+,\ D^0,\ D^{*+},\ D^{*0}; \\
\overline{D}(q\overline{c}) &:= D^-,\ \overline{D}^0,\ D^{*-},\ \overline{D}^{*0}; \\
D_s(\overline{s}c) &:= D_s^+,\ D_s^{*+}; \\
\overline{D}_s(s\overline{c}) &:= D_s^-,\ D_s^{*-}; \\
J/\psi(\overline{c}c) &:= \eta_c,\ J/\psi; \qquad (3)
\end{aligned}$$

Thus the number of directly produced mesons reads as

$$\begin{aligned}
\pi\,(q\overline{q}) &= C_\pi \cdot (b_q\, q) \cdot (b_{\overline{q}}\, \overline{q}) & J/\psi\,(c\overline{c}) &= C_{J/\psi} \cdot (b_c\, c) \cdot (b_{\overline{c}}\, \overline{c}) \\
K\,(q\overline{s}) &= C_K \cdot (b_q\, q) \cdot (b_{\overline{s}}\, \overline{s}) & D\,(\overline{q}c) &= C_D \cdot (b_{\overline{q}}\, \overline{q}) \cdot (b_c\, c) \\
\overline{K}\,(\overline{q}s) &= C_{\overline{K}} \cdot (b_{\overline{q}}\, \overline{q}) \cdot (b_s\, s) & \overline{D}\,(q\overline{c}) &= C_{\overline{D}} \cdot (b_q\, q) \cdot (b_{\overline{c}}\, \overline{c}) \\
\phi\,(s\overline{s}) &= C_\phi \cdot (b_s\, s) \cdot (b_{\overline{s}}\, \overline{s}) & D_s\,(\overline{s}c) &= C^s_D \cdot (b_{\overline{s}}\, \overline{s}) \cdot (b_c\, c) \\
& & \overline{D}_s\,(s\overline{c}) &= C^s_{\overline{D}} \cdot (b_s\, s) \cdot (b_{\overline{c}}\, \overline{c}) \qquad (4)
\end{aligned}$$

As a straightforward extension to the ALCOR model, the non-linear coalescence factors b_q, b_s, b_c and the $b_{\overline{q}}$, $b_{\overline{s}}$, $b_{\overline{c}}$ are determined unambiguously from the requirement that the number of the constituent quarks and anti-quarks do not change during the hadronization, and that all initially available quarks and anti-quarks have to end up in the directly produced hadrons. This constraint is a basic assumption in all models of quark coalescence. The correct quark counting yields to the following equations, expressing the conservation of the number of quarks:

$$\begin{aligned}
q &= 3\ N\,(qqq) + 2\ Y\,(qqs) + \Xi\,(qss) + K\,(q\overline{s}) + \pi\,(q\overline{q}) + \\
&\quad +2\ Y_c\,(qqc) + \Xi_c\,(qsc) + \Xi_{cc}\,(qcc) + \overline{D}\,(q\overline{c}) \qquad (5) \\
\overline{q} &= 3\ \overline{N}\,(\overline{qqq}) + 2\ \overline{Y}\,(\overline{qqs}) + \overline{\Xi}\,(\overline{qss}) + \overline{K}\,(\overline{q}s) + \pi\,(q\overline{q}) + \\
&\quad +2\ \overline{Y}_c\,(\overline{qqc}) + \overline{\Xi}_c\,(\overline{qsc}) + \overline{\Xi}_{cc}\,(\overline{qcc}) + D\,(\overline{q}c) \qquad (6) \\
s &= 3\ \Omega\,(sss) + 2\ \Xi\,(qss) + Y\,(qqs) + \overline{K}\,(\overline{q}s) + \phi\,(s\overline{s}) + \\
&\quad +2\ \Omega_c\,(ssc) + \Xi_c\,(qsc) + \Omega_{cc}\,(scc) + \overline{D}_s\,(s\overline{c}) \qquad (7) \\
\overline{s} &= 3\ \overline{\Omega}\,(\overline{sss}) + 2\ \overline{\Xi}\,(\overline{qss}) + \overline{Y}\,(\overline{qqs}) + K\,(q\overline{s}) + \phi\,(s\overline{s}) + \\
&\quad +2\ \overline{\Omega}_c\,(\overline{ssc}) + \overline{\Xi}_c\,(\overline{qsc}) + \overline{\Omega}_{cc}\,(\overline{scc}) + D_s\,(\overline{s}c) \qquad (8) \\
c &= 3\ \Omega_{ccc}\,(ccc) + 2\ \Xi_{cc}\,(qcc) + \Lambda_c\,(qqc) + D\,(\overline{q}c) + J/\psi\,(c\overline{c}) + \\
&\quad +2\ \Xi_{cc}\,(scc) + \Lambda_c\,(qsc) + \Lambda_c\,(ssc) + D_s\,(\overline{s}c) \qquad (9) \\
\overline{c} &= 3\ \overline{\Omega}_{ccc}\,(\overline{ccc}) + 2\ \overline{\Xi}_{cc}\,(\overline{qcc}) + \overline{\Lambda}_c\,(\overline{qqc}) + \overline{D}\,(q\overline{c}) + J/\psi\,(c\overline{c}) + \\
&\quad +2\ \overline{\Xi}_{cc}\,(\overline{scc}) + \overline{\Lambda}_c\,(\overline{qsc}) + \overline{\Lambda}_c\,(\overline{ssc}) + \overline{D}_s\,(s\overline{c}) \qquad (10)
\end{aligned}$$

These equations for q, s, c and ($\overline{q}$, $\overline{s}$, $\overline{c}$) determine the six b_i normalization factors — which are not free parameters. These constraints, together with the prescription of the coalescence factors C_i, complete the description of hadron production from charmed quark matter by quark coalescence, and define the ALCOR$_c$ model.

In this paper, we will evaluate only the simplest predictions from ALCOR$_c$, by considering ratios of the number of particles to the number of anti-particles and by assuming the symmetry of the coalescence process for charge conjugation, extending the results of ref. [6] to the case of charmed quarks, mesons and baryons.

Assuming that the coalescence coefficients C for hadrons are equal to that for the corresponding anti-particles, e.g. $C_\Lambda = C_{\overline{\Lambda}}$, the following relations were obtained for the ratio of light and strange antibaryons and baryons [6]:

$$\frac{\overline{N}\,(\overline{qqq})}{N\,(qqq)} = \left[\frac{b_{\overline{q}}\,\overline{q}}{b_q\,q}\right]^3 \tag{11}$$

$$\frac{\overline{Y}\,(\overline{qqs})}{Y\,(qqs)} = \left[\frac{b_{\overline{q}}\,\overline{q}}{b_q\,q}\right]^2 \cdot \left[\frac{b_{\overline{s}}\,\overline{s}}{b_s\,s}\right] \tag{12}$$

$$\frac{\overline{\Xi}\,(\overline{qss})}{\Xi\,(qss)} = \left[\frac{b_{\overline{q}}\,\overline{q}}{b_q\,q}\right] \cdot \left[\frac{b_{\overline{s}}\,\overline{s}}{b_s\,s}\right]^2 \tag{13}$$

$$\frac{\overline{\Omega}\,(\overline{sss})}{\Omega\,(sss)} = \left[\frac{b_{\overline{s}}\,\overline{s}}{b_s\,s}\right]^3 \tag{14}$$

Inspecting eqs. (11)-(14) one can recognize, that the kaon to anti-kaon ratio $\mathcal{S}^{qs}$ has a special role as it acts as a stepping factor that connects various antibaryon to baryon rations,

$$\mathcal{S}^{qs} \equiv \frac{K\,(q\overline{s})}{\overline{K}\,(\overline{q}s)} = \left[\frac{b_q\,q}{b_{\overline{q}}\,\overline{q}}\right] \cdot \left[\frac{b_{\overline{s}}\,\overline{s}}{b_s\,s}\right] \quad . \tag{15}$$

This factor $\mathcal{S}^{qs}$ substitutes a light quark with a strange quark in the antibaryon to baryon ratios. Thus it shifts the antibaryon to baryon ratios and changes their strangeness content by one unit, as the following relations display:

$$\mathcal{S}^{qs}\left[\frac{\overline{N}}{N}\right] = \frac{\overline{Y}}{Y} \tag{16}$$

$$\mathcal{S}^{qs}\mathcal{S}^{qs}\left[\frac{\overline{N}}{N}\right] = \frac{\overline{\Xi}}{\Xi} \tag{17}$$

$$\mathcal{S}^{qs}\mathcal{S}^{qs}\mathcal{S}^{qs}\left[\frac{\overline{N}}{N}\right] = \frac{\overline{\Omega}}{\Omega} \tag{18}$$

The inverse factor, $\mathcal{S}^{sq} = (\mathcal{S}^{qs})^{-1}$ decreases the strangeness content and increases the number of light quarks in the antibaryon to baryon ratios. Note that these relations hold between the ratios of the directly produced anti-baryons to baryons and that the number of observed anti-baryons and baryons have to be corrected to the various chains of resonance decays [6].

Extending the above ALCOR model to the case of charmed baryons and antibaryons, further relations are obtained:

$$
\begin{aligned}
\frac{\overline{Y}_c\,(\overline{qqc})}{Y_c\,(qqc)} &= \left[\frac{b_{\overline{q}}\,\overline{q}}{b_q\,q}\right]^2 \cdot \left[\frac{b_{\overline{c}}\,\overline{c}}{b_c\,c}\right] &\qquad \frac{\overline{\Xi}_c\,(\overline{qsc})}{\Xi_c\,(qsc)} &= \left[\frac{b_{\overline{q}}\,\overline{q}}{b_q\,q}\right] \cdot \left[\frac{b_{\overline{s}}\,\overline{s}}{b_s\,s}\right] \cdot \left[\frac{b_{\overline{c}}\,\overline{c}}{b_c\,c}\right] \\
\frac{\overline{\Xi}_{cc}\,(\overline{qcc})}{\Xi_{cc}\,(qcc)} &= \left[\frac{b_{\overline{q}}\,\overline{q}}{b_q\,q}\right] \cdot \left[\frac{b_{\overline{c}}\,\overline{c}}{b_c\,c}\right]^2 &\qquad \frac{\overline{\Omega}_c\,(\overline{ssc})}{\Omega_c\,(ssc)} &= \left[\frac{b_{\overline{s}}\,\overline{s}}{b_s\,s}\right]^2 \cdot \left[\frac{b_{\overline{c}}\,\overline{c}}{b_c\,c}\right] \\
\frac{\overline{\Omega}_{ccc}\,(\overline{ccc})}{\Omega_{ccc}\,(ccc)} &= \left[\frac{b_{\overline{c}}\,\overline{c}}{b_c\,c}\right]^3 &\qquad \frac{\overline{\Omega}_{cc}\,(\overline{scc})}{\Omega_{cc}\,(scc)} &= \left[\frac{b_{\overline{s}}\,\overline{s}}{b_s\,s}\right] \cdot \left[\frac{b_{\overline{c}}\,\overline{c}}{b_c\,c}\right]^2
\end{aligned} \tag{19}
$$

These ratios and the ratios from eqs. (11)-(14) can be organized into a special structure displayed in Fig.1. We can introduce two more factors $\mathcal{S}^{sc}$ and $\mathcal{S}^{cq}$ constructed as in eq.(15) but from the ratios of charmed mesons:

$$\mathcal{S}^{sc} \equiv \frac{\overline{D}_s\,(s\overline{c})}{D_s\,(\overline{s}c)} = \left[\frac{b_s\,s}{b_{\overline{s}}\,\overline{s}}\right] \cdot \left[\frac{b_{\overline{c}}\,\overline{c}}{b_c\,c}\right] \tag{20}$$

$$\mathcal{S}^{cq} \equiv \frac{D\,(\overline{q}c)}{\overline{D}\,(q\overline{c})} = \left[\frac{b_c\,c}{b_{\overline{c}}\,\overline{c}}\right] \cdot \left[\frac{b_{\overline{q}}\,\overline{q}}{b_q\,q}\right] \tag{21}$$

The factor $\mathcal{S}^{sc}$ substitutes a strange quark with a charm one and the factor $\mathcal{S}^{cq}$ changes the charm quark into a light one. These properties lead to the following identity:

$$\mathcal{S}^{qs} \cdot \mathcal{S}^{sc} \cdot \mathcal{S}^{cq} \equiv 1 \tag{22}$$

This identity can be rewritten as an identity between the mesonic ratios:

$$\frac{\overline{D}_s/D_s}{\overline{D}/D} = \overline{K}/K \tag{23}$$

A comparison of this simple relation with experimental data could serve as test of quark matter formation and coalescence type rehadronization in heavy ion collisions.

The inverse of the step factors is defined as $\mathcal{S}^{ji} = (\mathcal{S}^{ij})^{-1}$. The structure of the antibaryon to baryon ratios in ALCOR$_c$ is visualized in a geometric manner in Fig. 1. This way, more complicated but definitely interesting relations can be obtained. Since the baryons with one charm quark (or antiquark) can be measured most easily, one may consider the following relations as candidates for an experimental test:

$$\frac{\overline{\Xi}_c\,(\overline{qsc})}{\Xi_c\,(qsc)} = \mathcal{S}^{qs}\left[\frac{\overline{Y}_c}{Y_c}\right] = \mathcal{S}^{qc}\left[\frac{\overline{Y}}{Y}\right] = \mathcal{S}^{sc}\left[\frac{\overline{\Xi}}{\Xi}\right] = \mathcal{S}^{sq}\left[\frac{\overline{\Omega}_c}{\Omega_c}\right]. \tag{24}$$

These yield the following simple relation between baryonic and mesonic ratios:

$$\frac{\overline{Y}/Y}{\overline{Y}_c/Y_c} = D_s/\overline{D}_s\ , \tag{25}$$

$$\frac{\overline{N}/N}{\overline{Y}_c/Y_c} = D/\overline{D}\ , \tag{26}$$

$$\frac{\overline{N}/N}{\overline{Y}/Y} = \overline{K}/K\ . \tag{27}$$

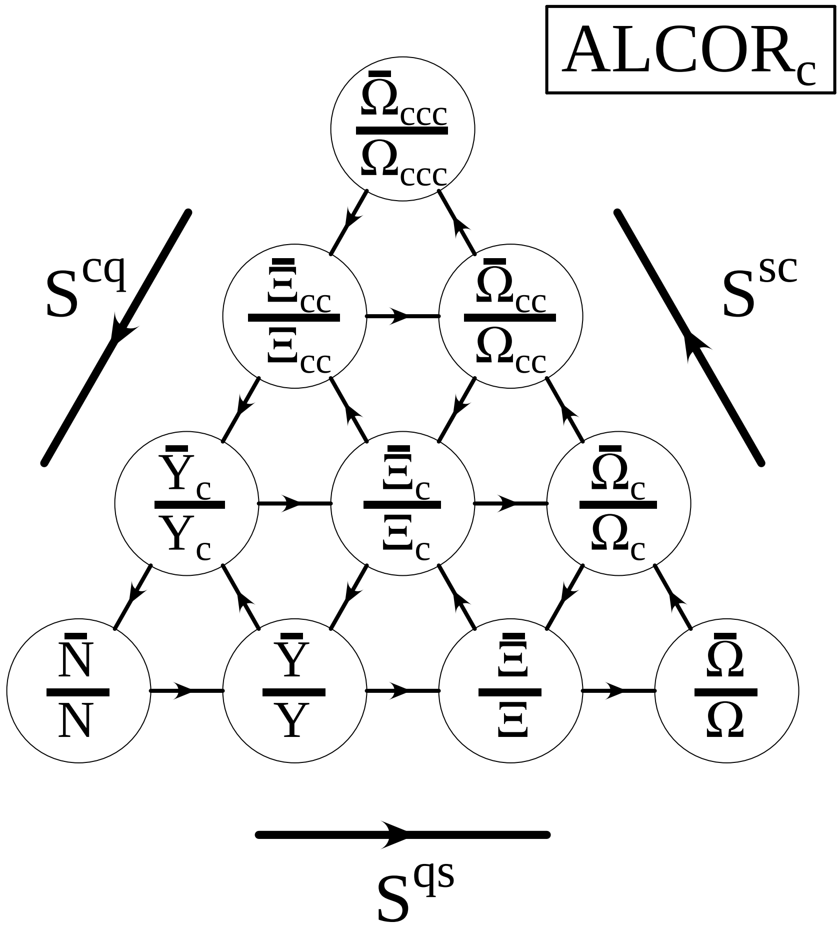

Fig. 1. The application of mesonic step factors $\mathcal{S}^{qs}$, $\mathcal{S}^{sc}$ and $\mathcal{S}^{cq}$ on the antibaryon to baryon ratios. The arrows are indicating the three corresponding directions of shifting.

A number of similar expressions can be derived from Figure 1, picking up a given ratio and following all the paths to reach that from its neighbors.

In summary , we have made simple predictions from the ALCOR$_c$ model, extending the ALCOR model of algebraic coalescence and rehadronization of quark matter to the case when charmed quarks and final state hadrons are present in a significant number. We found that the various $\overline{M}/M$ mesonic ratios connect different $\overline{B}/B$ ratios. The agreement between the obtained theoretical relations and those in the measured data could serve as proof or disproof of the formation of quark matter in heavy ion collisions followed by a fast hadronization via quark coalescence. The predictions made in this paper are independent from the detailed values of coalescence coefficients, we have assumed only their symmetry for charge conjugation. The calculations of the absolute numbers of produced particles from ALCOR$_c$ requires the specification of these coalescence coefficients from calculations of cross-sections.

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